Towards an integrated high resolution TOF PET system

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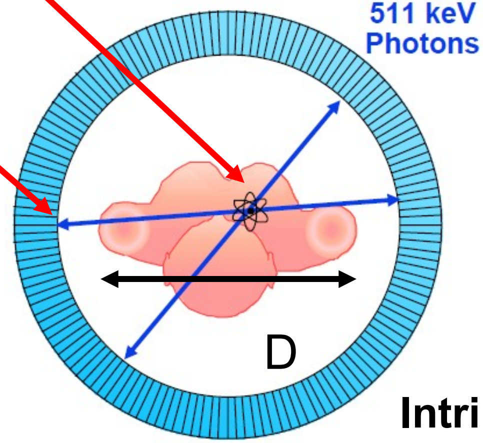
Pico-second timing and TOF PET

Pico-second timing of FWHM Δt can provide:

Coordinate along the 2-photons : FWHM improved by $2D/c\Delta t$
Transverse position using T Lines



Intrinsic resolution (FWHM)
e+ / e- 1mm (Δt=66ps)
$\delta\ \Theta$ 4mR

- **Improve image quality,**
- **Speed up the convergence of the reconstructing algorithms**

Best resolution of **500-300ps** **FWHM, 7.5-4.5cm with LSO or $LaBr_3$ crystals**
<1mm transverse (T-lines), centroids in the axial direction

TOF vs No-TOF PET

- **Surti et al. NSS MIC 2006**

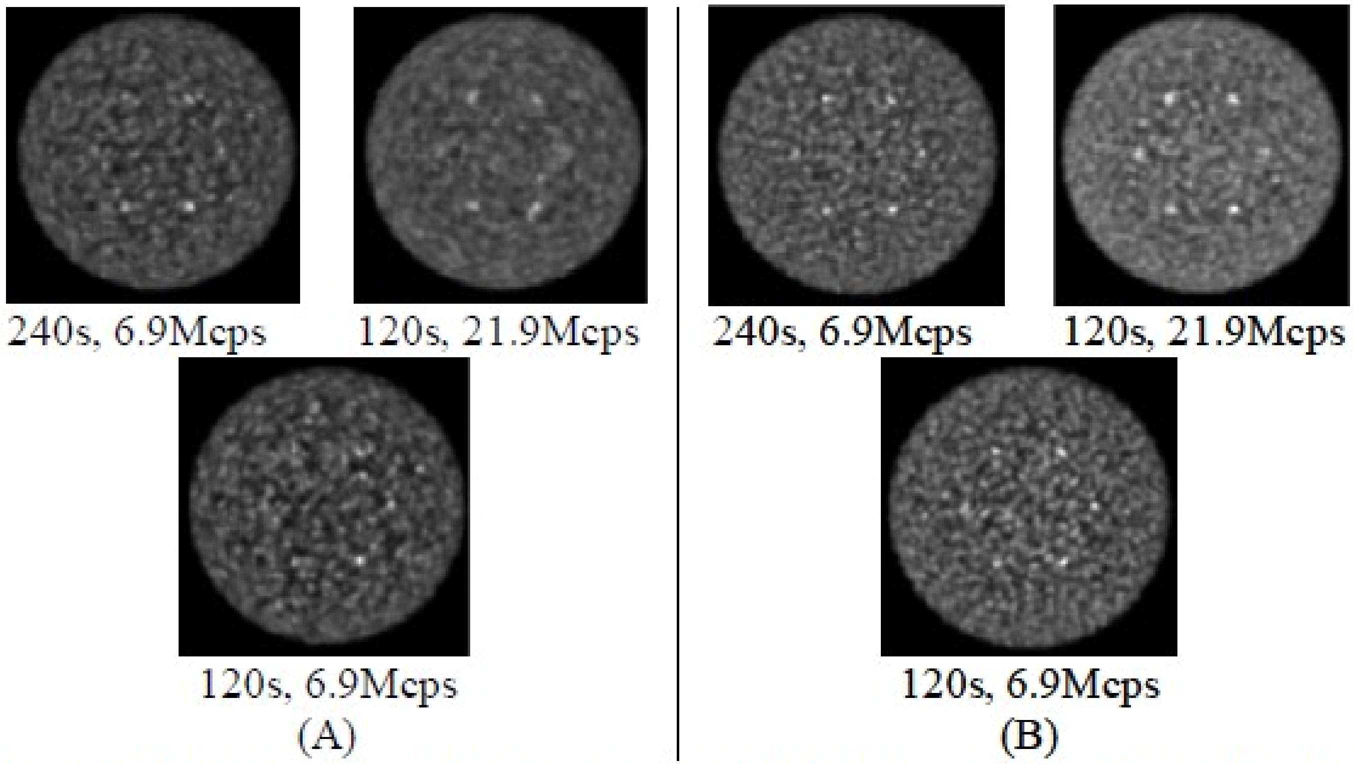


Fig. 6. Transverse slices for the reconstructed images of the 35-cm diameter lesion phantom with Non TOF (A) and TOF (B) reconstructions.

TOF: $\Delta x = c \Delta t/2$

Δt due mainly to crystal

Recent progress

INNOTEP Project

G Montarou

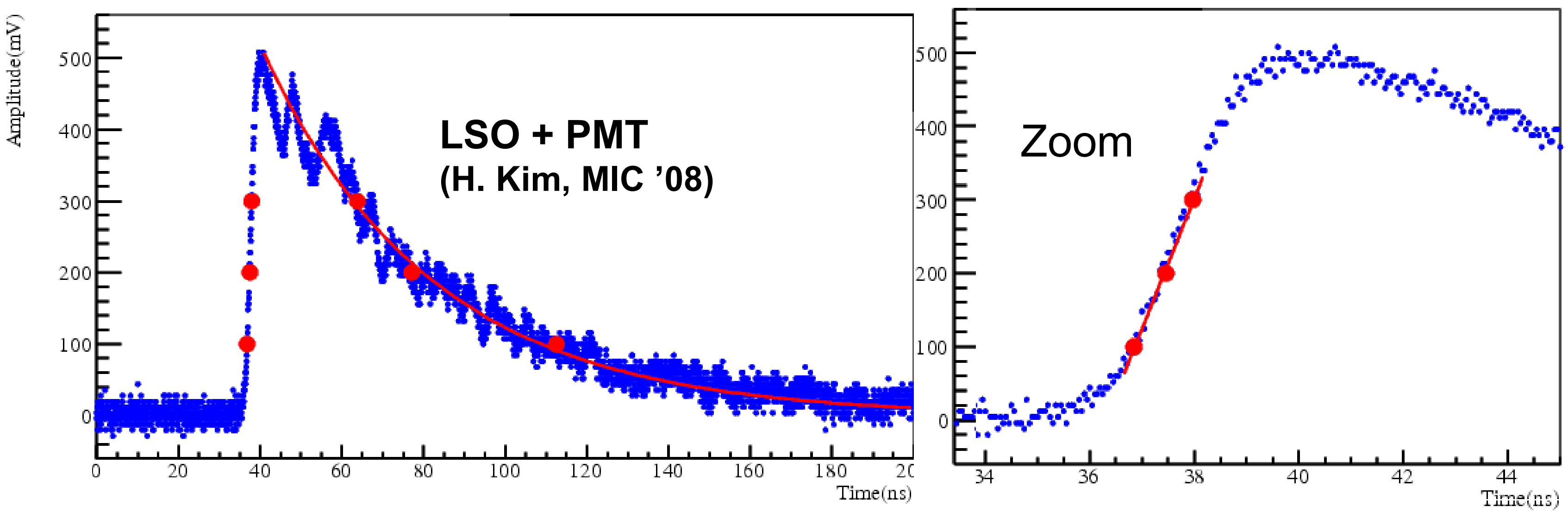
Monte Carlo assessment of time-of-flight benefits on the LYSO-based discovery with PET/ CT scanner
Geramifar, P. et al
Biomedical Imaging: From Nano to Macro, 2008. Volume , Issue , 14-17 May 2008 pp364-367

Potential Advantages of Digitally Sampling Scntillation Pulses in Timing Determination in PET
Xie Quingguo et al
IEEE Trans on Nucl Sci 2008

Crystals signals

Block/Single Crystal	Timing res. (ps)	Light output 10^4 ph/MeV	Energy res. @ 511 KeV (%)
BGO	3000	0.8	12
LSO	550	2.5	10
LuI3	125	9	6
$LaBr_3$	350/70	6	3

- W. Moses, Oct 2008



H Kim, Chicago

LSO+PMT rise time is ~1.4ns LSO only is 1ns

Timing and position resolution limits for PET

-1 Along the γ ray axis

Limited by crystals timing resolution
LuI_3 : 125ps resolution with 3 times more photons than LSO, but are too expensive.
$LaBr_3$ provides 350ps resolution at 2/3 less photons, good trade-off, compared to LSO

350ps is 5.2cm FWHM

-2 Transverse

Micro-Channel Plates + transmission lines read with sampling chips in the 10GHz range can provide 10ps timing (laser), so transverse position measurements to 500μ m FWHM, assuming T-lines velocity c/3, and crystal resolution not contributing since two ends signals are correlated. Crystal size quantization to be added:

total is 650 + 500 =820 μ m FWHM

-3 Axial

Crystal cannot be smaller than 1 x 1mm^2 (650μ m FWHM)

Fast Photo-detectors

30PEs	Time (FWHM)	Position (FWHM)	Area	Pix size mm^2
(Ma)PMT	60ps	9.1mm	2” x 2”	6 x 6
SiPM	70ps	10.6mm	linear array, 32ch	1 x 1
MCP	25ps	3.8mm	2” x 2”	1.6 x 1.6

MCP best for large size, timing and pixel size

Position + time with Transmission Lines

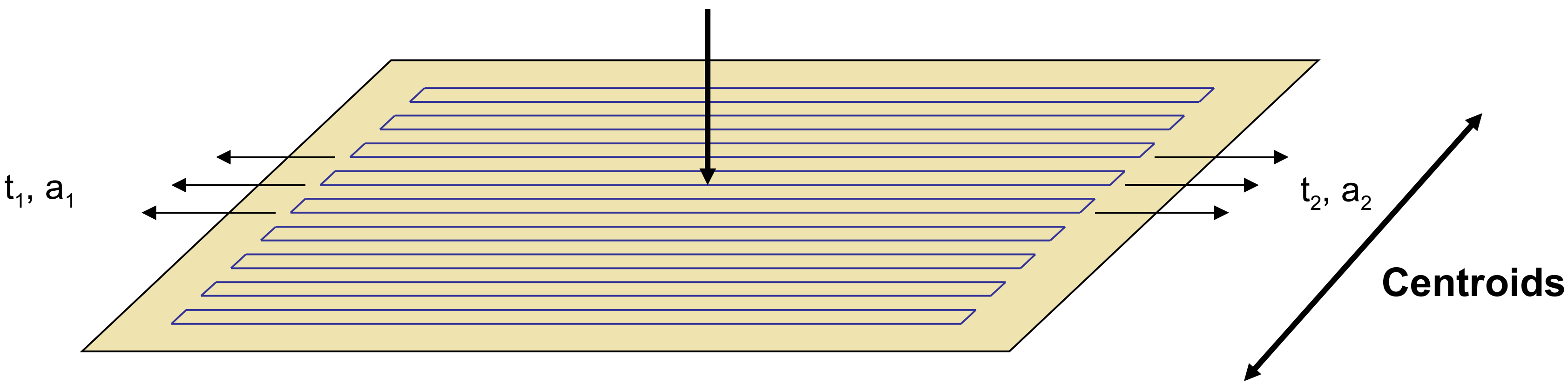
- Pico-second timing provides

  - **Fast timing**
  - **Transmission lines readout.**

    Transverse position along the line

    Axial coordinate from centroids

Less electronics channels for large area sensors



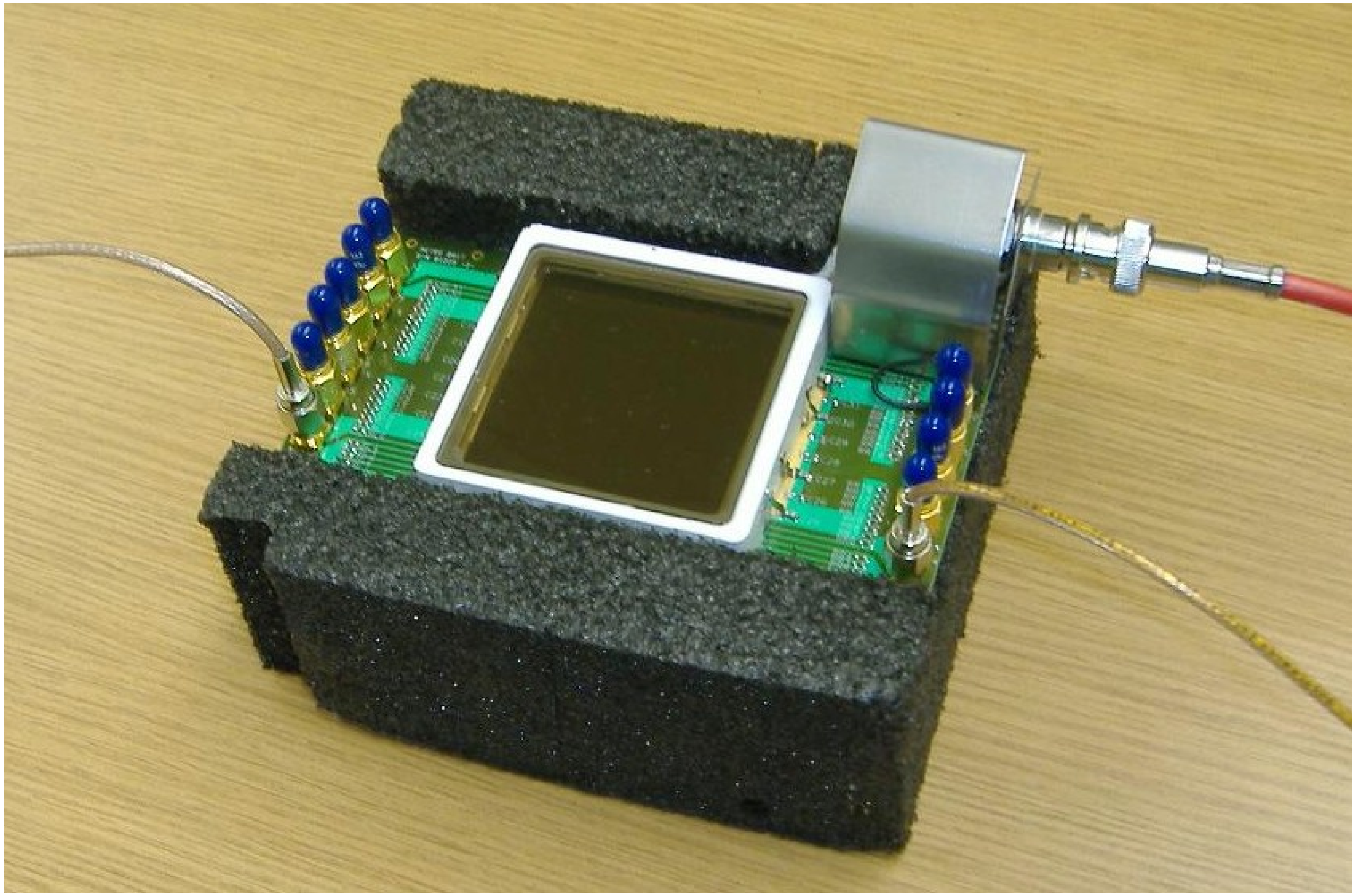
$\frac{1}{2}$ **$(t_1 + t_2)$ = time**

$t_1 - t_2 / t_1 + t_2$ = transverse position

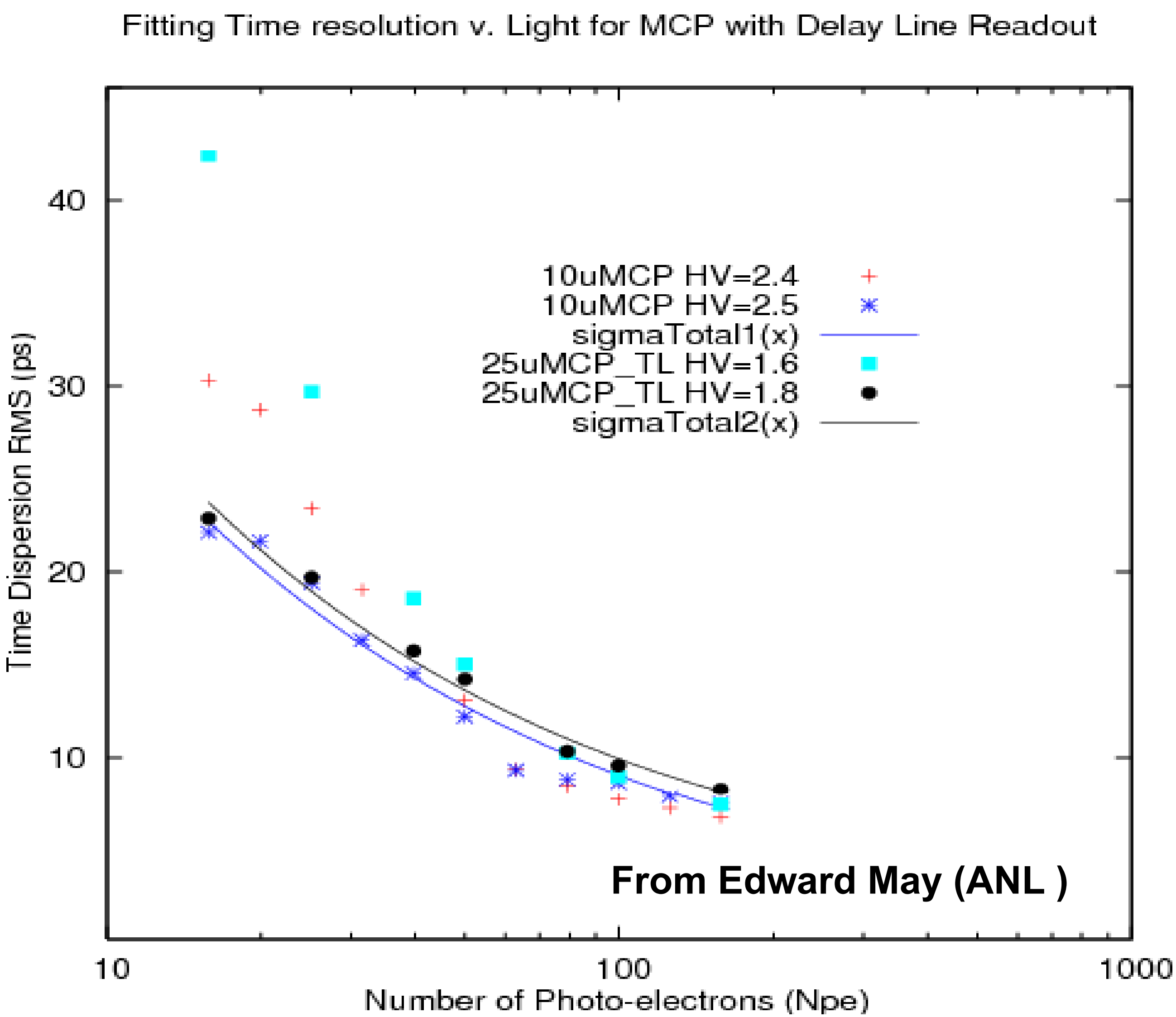
$\Sigma\ \alpha_i\, a_i / \Sigma\ \alpha_i$ = axial position

MCP + TLs

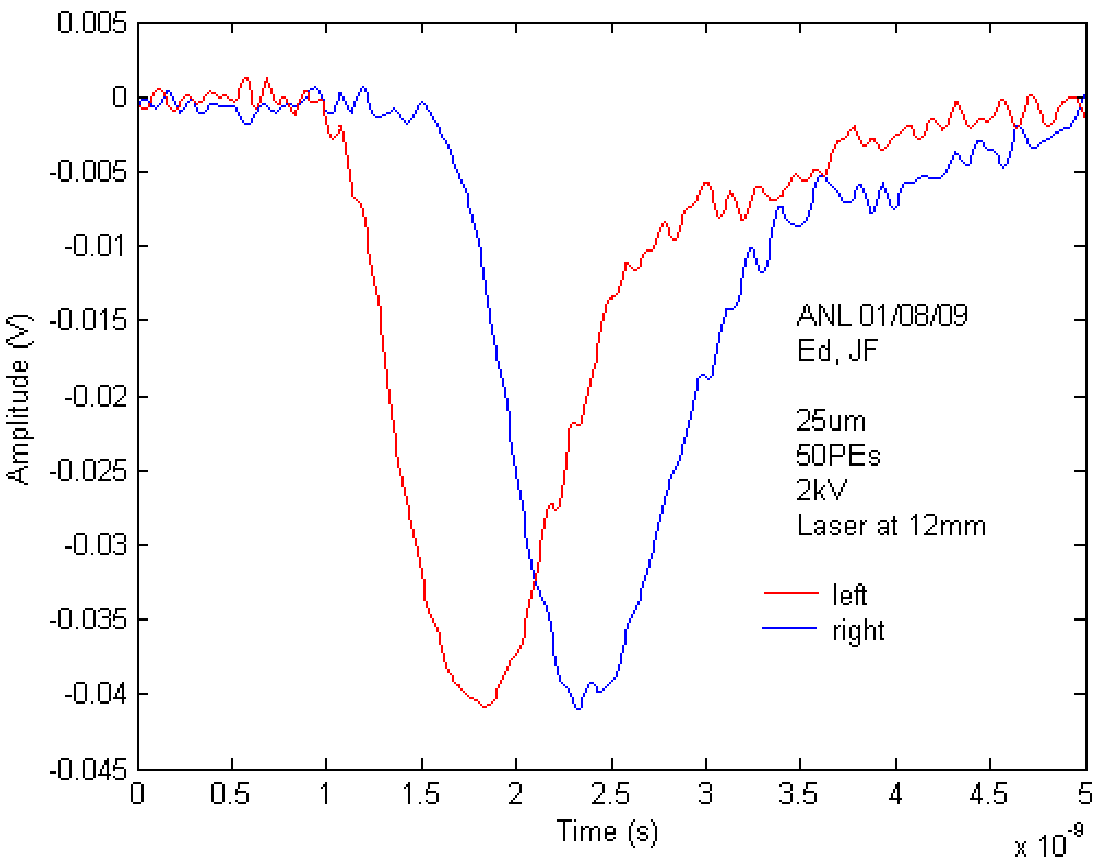
Laser @ 50PEs: 70ps FWHM one-side   10ps diff



Timing with laser on 2” x 2” MCPs
(TLs on Printed Circuit Board)



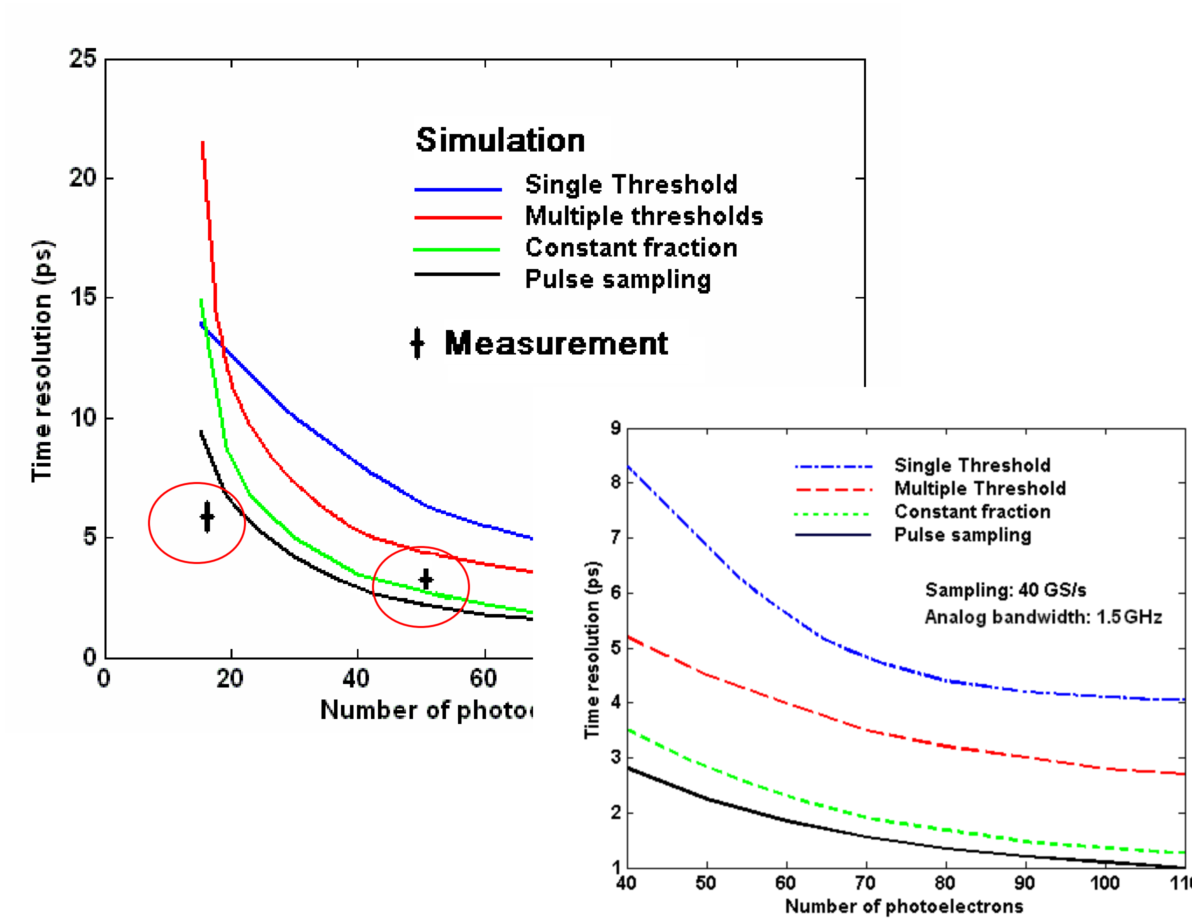
T-lines two-ends with 25µ m MCP



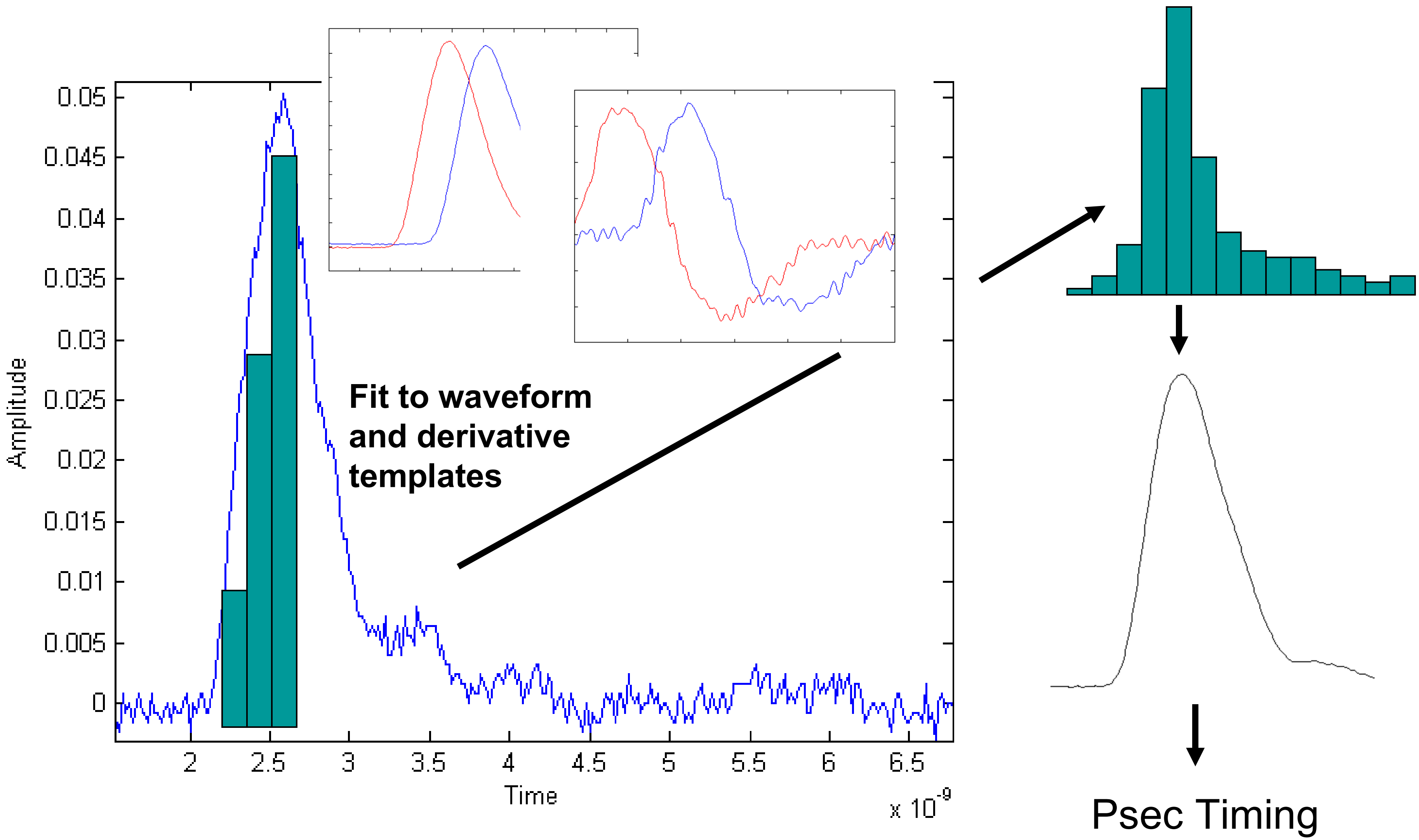
25 µ m pore MCP signal at the output of a ceramic transmission line
Laser 408nm, 50Ω , no amplification

Signal processing for pico-second timing

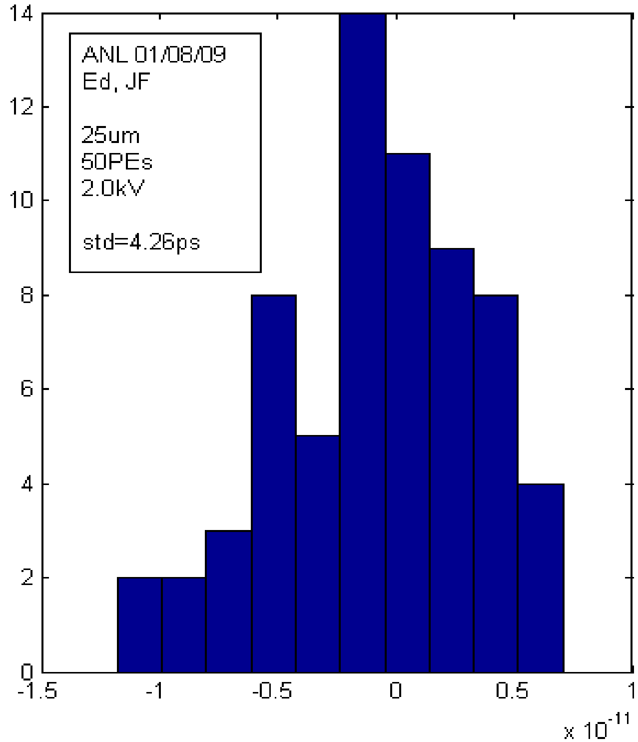
- Multi-threshold
- Constant Fraction
- Sampling and
  Waveform analysis

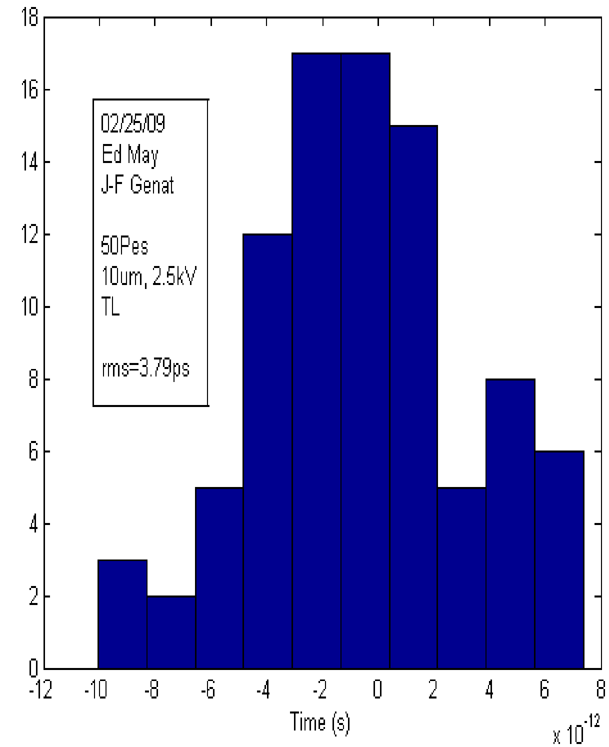


Pulse Sampling and Waveform Analysis



MCP + TL (laser)



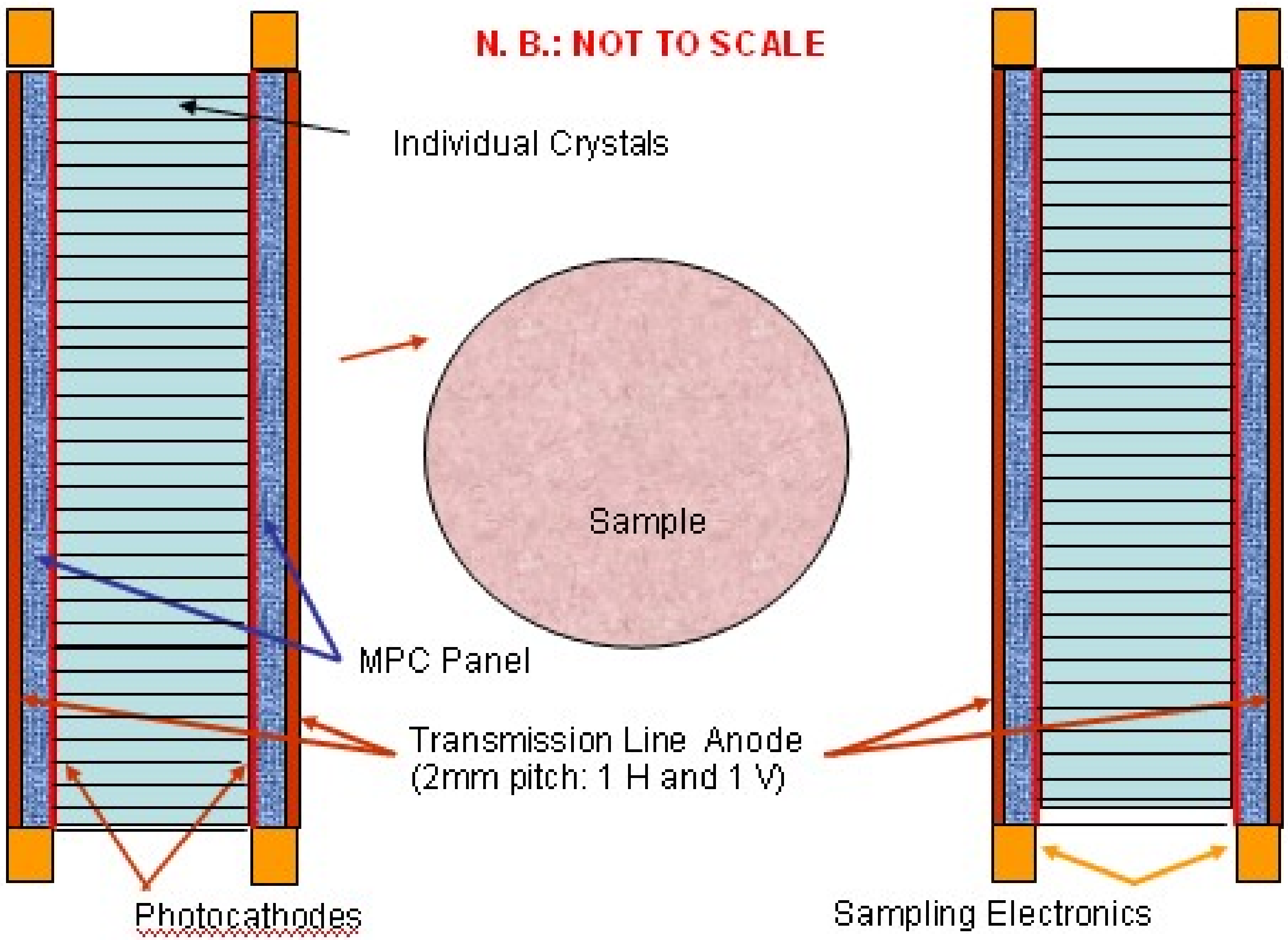


25um tube, 50 PEs
FWHM = 10ps 500 μ m

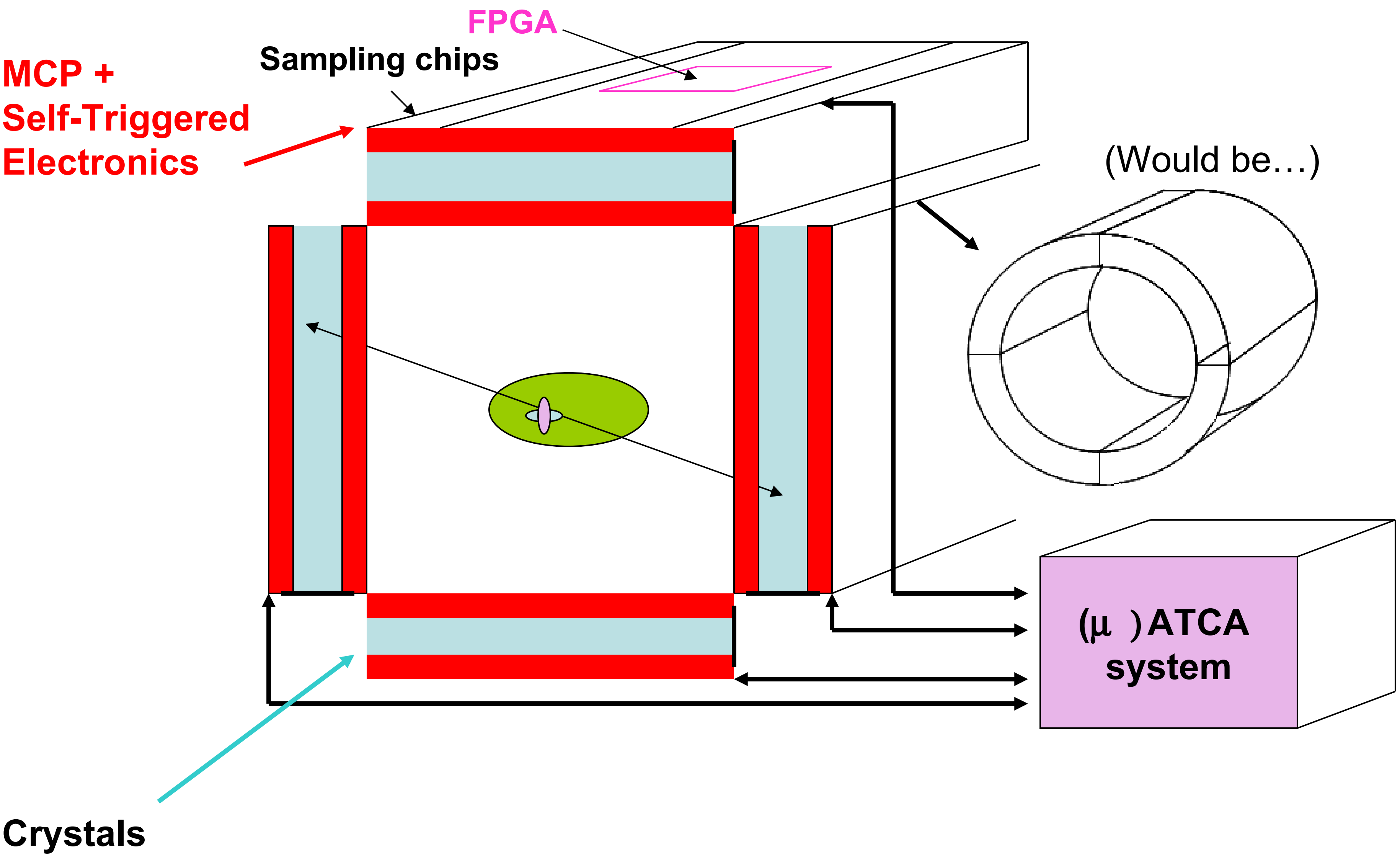
10um tube
FWHM = 8.9ps **450 μ m**

NB. Not obtained from crystal signals, but laser fast light source

A MCP based Micro-PET system (H. Frisch)



A PET system with on-detector electronics



Self-triggered Readout Architecture

Strategy: Extract from the front-end relevant data only

- Sample and overwrite continuously in the 10 GS/s range (analog)
- Digitize in the front-end any activity above a given threshold
  - Using front-end sampling chip triggering capability

    and *optionally*
  - Process on front-end with FPGAs to extract time, amplitude
- Send to system crate for processing via a few optical/copper links
- Process data in ATCA System crate
  - Coincidences, reconstruction, calibrations
- Timing distribution from system crate needed with a ~10ps stability
  - Not too critical on a relatively small system

Sampling Chips

State of the art:

	Sampling	Bandwidth	Dyn. range	Depth	PLL	ADC	Trigger
	GHz	GHz	bits			bits	
G. Varner (Hawaii)	6	1.0	10	1024	no	12	experience
S. Ritt (PSI)	6	.8	11.5	256	3.9ps		no
D. Breton (Orsay) +	2.5	.3	13.4	250	20ps	no	no
E. Delagnes (Saclay)							

130nm CMOS Timing Sampling chip

- 40 GHz sampling rate
- Analog bandwidth ~ 1.5 GHz
- Triggered mode
- Depth 256

- On-chip 10-bit ADC

Presently under development a U Chicago

Dataflow

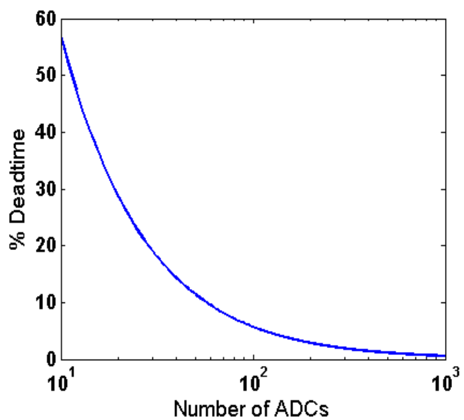
Dataflow

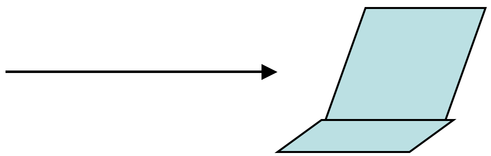
- **Assume 64 samples (taken for 1.6 ns at 20GS/s), in nine adjacent crystals**
- **Assume 1MCps rate, a safety factor of four (noise + system noise)**
- **Each of four sections linked to one µ TCA crate runs at:**

Without sample processing
4M Cps x 2 x 4 layers x 9 crystals x 64 samples x 8bits = 72 Gb/s

With sample processing (FPGA)
4M Cps x 4 layers x 9 crystals x 4 words x 8bits = 4.6 Gb/s

Deadtime





ATCA System

- **Use ATCA Advanced Telecom Computing Architecture**

  - ATCA with the full sampled data readout option (>70 Gb/s input)
  - Use fibers at 10 Gb/s (Gigabit Ethernet)

- Micro-TCA system may be sufficient in the case of on-detector digital processing (> 4 G/s input)
- A few serial frast cables sufficient

High resolution image output

Conclusion

Use of an integrated PET system making use of Micro-channel Plates sensors, transmission lines readout, custom sampling electronics, and digital signal processing allows :

- Extracting timing to sub-millimeter precision in the transverse dimension with a reduced number of electronics channel,

- Reducing the amount of data to be read and processed off-line by one order of magnitude at least.

Extra slides

10um tube

- Tuning the HV at 2.5 kV to have the same MCP pulse amplitude as the 25um tube at 2kV (30mV)

50PEs, 2.5kV
std=3.82ps
vs 2.5ps (simulation)

18PEs, 2.5 kV
std = 6.05ps
vs 7ps (simulation)